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BENEFITS OF OVERLOAD FOR FATIGUE CRACKING AT A NOTCH

J. H. Underwood
J. A. Kapp

May 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
LARGE CALIBER WEAPON SYSTEMS LABORATORY
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Tests are described which measure the effect of compression overload on fatigue crack initiation and growth from a 0.1 mm radius notch in alloy steel K_{Ic} specimens. Other tests are described which measure the effect of tension overload on fatigue crack initiation and growth from a 3.4 mm root radius notch in similar specimens. The effect of overload on the number of cycles required for crack growth is described for both types of tests in relation to a residual stress model.

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1. INTRODUCTION

There are situations in which a fatigue crack at a notch is required and others in which a fatigue crack is to be avoided. In either case the application of an overload to the structure or specimen containing the notch can be of benefit. When a fatigue crack is required, such as when precracking the specimens required in some fracture tests, a compression overload applied to the notched specimen can result in faster formation of a crack at the root of the notch. One of the objectives of this paper is to describe compressive overload tests performed with some fracture toughness specimens and show the effect of overload on fatigue crack initiation and growth from the notch.

When initiation and growth of a fatigue crack should be avoided, such as at a fillet or corner in a loaded structured component, a tensile stress overload applied in the vicinity of the fillet or corner can serve to prevent or delay the initiation and growth of a crack. The second objective here is to describe and analyze laboratory tests which simulate a component with a notch subjected to a tensile stress overload.

2. OVERLOAD TO INDUCE CRACKS

A few laboratories apply compressive overloads to fracture test specimens in order to save time in fatigue precracking. But the overload procedure and the effect on precracking have not been described in the literature, and the overload procedure is not generally used. This lack of information and use of overloads prompted this effort.

2.1 Test Procedure

The general test procedure was the compressive overload procedure commonly used in our laboratory when precracking plane strain fracture toughness, K_{Ic}, specimens. In brief, the procedure is a single compression load applied to the notched K_{Ic} specimen using twice the maximum load to be used in precracking. Details will follow. A total of thirty K_{Ic} specimens were tested. The specimens were the C-shaped geometry described in ASTM Method for Plane Strain Fracture Toughness of Metallic Materials, E399-78 and shown in Figure 1. The specimens were taken from cylindrical steel cannon forgings of 44 mm inner radius, 85 or 120 mm outer radius. The steel is a Ni-Cr-Mo-V composition similar to A1S1 4335, heat treated to a yield strength range of 1150 to 1200 MPa. Table I lists some additional test conditions.

Three groups of ten specimens were tested, as indicated in Table I. The group 1 specimens are of thickness, B = 25.4 mm and nominal depth, W = 42 mm; they were taken in pairs from five forgings. The group 2 and 3 specimens are of B = 38.1 mm and nominal W = 74 mm, and they were taken one per forging from twenty forgings. All specimens were tested with as-forged inner and outer diameters, so dimensions vary somewhat. The variation can be noted in the W values listed in Table I. Details of the notch tip configuration are a 90° included angle with a 0.13 mm root radius as measured on a sampling of specimens using an optical comparitor.

In each group of ten specimens, five were overloaded, five were not. Using nominal specimen dimensions and the overloads listed in Table I, the K values corresponding to the overloads are 86 $MPa\sqrt{m}$ for group 1 and 2 specimens and 66 MPa$\sqrt{m}$ for group 3 specimens. These values were calculated using the following K expression for the C-shaped specimen,[1]

$$K = \frac{P}{B\sqrt{W}} [3\ X/W + 1.9 + 1.1\ a/W][1 + .25(1-a/W)^2(1-r_1/r_2)]F(a/W)$$

where (1)

$$F(a/W) = \frac{\sqrt{a/W}}{(1-a/W)^{3/2}} (3.74 - 6.30\ a/W + 6.32(a/W)^2 - 2.43(a/W)^3)$$

which applies for $0.2 \leq a/W \leq 1$, $0 \leq X/W \leq 1$, $0 \leq r_1/r_2 \leq 1$. See Figure 1 for definition of terms. The maximum tension load in fatigue was always one half of the overload, so at the start of the fatigue loading, the nominal K_{max} were 43 MPa$\sqrt{m}$ for groups 1 and 2 and 33 MPa$\sqrt{m}$ for group 3. The specific values of K_{max} at the start of fatigue loading, including the effects of variations in W, relative loading hole position, X/W, and notch length, a/W, were calculated using Eq. (1) and are listed in Table I. As can be determined from Table I, W varies by as much as ± 3%; the quantities X/W and a/W vary by like amounts. This leads to a variation in K_{max} at the start of fatigue loading of as much as ± 8%. For all tests K_{min} was one tenth of K_{max}. Fatigue loading was continued until about 3 mm of crack growth had occurred.

In summary, the tests provide for the determination of the effect of compression overload on fatigue crack initiation from a notch in a K_{Ic} specimen, considering two different specimen sizes and two different levels

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[1]Kapp, J. A., Newman, J. C., Underwood, J. H., "A Wide Range Stress Intensity Factor Expression for the C-Shaped Specimen," Journal of Testing and Evaluation, to be published.

of overload and fatigue loading. In addition the effect of overload on the subsequently measured K_{Ic} can be determined.

2.2 Results

The results from the compression overload tests are presented in Table II. For each of the thirty tests, crack growth data, number of fatigue cycles required for growth, and the measured K_{Ic} are listed. The crack growth data is, first, Δa, the average amount of fatigue crack growth beyond the notch tip, as described in ASTM Method E399. Three measurements, at locations corresponding to 1/4, 1/2, and 3/4 B, were made on the fracture surface after the K_{Ic} test and averaged to obtain Δa. Values of Δa vary between 2.1 and 3.5 mm. The smaller of the two surface crack growth measurements also was made, divided by Δa and listed as $\Delta a_{min}/\Delta a$. This ratio provides a quantitative measure of the crack-front symmetry; because Δa_{min} is normalized by Δa, the ratio includes little or no effect of the variation in Δa noted above. A high value of $\Delta a_{min}/\Delta a$ corresponds to a relatively straight, symmetrical crack front with no more curvature than the normally observed lagging of the crack front at both specimen surfaces. A low value of this ratio indicates that the crack front lags more than normal at one surface. In groups 1 and 2, the specimens with the higher K_{max} in fatigue, there appears to be no significant effect of overload on crack front symmetry as measured by $\Delta a_{min}/\Delta a$. In group 3, the lower K_{max} specimens, there is indeed an effect of overload on symmetry; without overload, the crack front is much more likely to lag significantly at one surface, which causes non-symmetry and a potentially poor fracture test.

The number of fatigue cycles N_i required to grow the crack to an average Δa of 0.25 mm determined from the two surface measurements and the number of cycles, N_f, required to grow the crack to the final Δa are listed in Table II. Note that the difference between these two numbers, N_f-N_i, is approximately constant for all tests. This means that the test conditions do not greatly affect crack growth from Δa = 0.25 to the final value, about 3 mm; the effects of the test conditions are apparently on the initiation and early growth of the crack. Considering the N_f data in Table II, all three groups of specimens show a significant decrease in N_f when overload is applied compared to the tests with no overload. This is particularly so for the group 3 tests at lower K_{max}. The last column of data in Table II is the results from K_{Ic} tests; there appears to be no significant effect of overload in K_{Ic}.

2.3 Statistical Analysis

To give a quantitative measure of the observed results, some statistical analysis was performed. The effect of overload on three parameters was analyzed; the number of fatigue cycles to initiate and grow the crack to Δa = 3 mm, N_f, the crack front shape as measured by $\Delta a_{min}/\Delta a$, and the fracture toughness, K_{Ic}. For each group of specimens the mean, μ, and standard deviation, σ, were determined for specimens with and without overload. These data are shown in Table III. Once the μ and σ are known for the two test conditions in each group a test statistic can then be calculated which is used to determine the probability that the two means represent the same population of data. To do this it is first necessary to determine if the measured data are normally distributed. The Kolmogorov-Smirnov test[2] was applied to each set of data to test for normality. This test compares the observed distribution to the theoretical normal distribution with the same μ and σ. If the maximum difference between the observed distribution and the theoretical distribution is less than a specified amount for the given sample size, then it can be stated with a 99% confidence level that the observed data are normally distributed. All six sub-groups of data met the Kolmogorov-Smirnov criterion.

The test statistic necessary to compare the two means is:

$$d = \frac{|\mu_{overload} - \mu_{no\ overload}|}{\sqrt{\sigma^2_{overload} + \sigma^2_{no\ overload}}} \tag{2}$$

where the subscripts correspond to the two test conditions compared. Once d is known we are able to determine the probability with a 99% confidence level that the means represent the same population of data through the use of "Operating Characteristic Curves" available in the literature.[3] These probabilities are shown in Table III as P_a, P_N, and P_K, the probabilities related to crack growth, fatigue cycles, and K_{Ic} data, respectively. They indicate that the overload data are a significantly different population and thus overload has a significant effect in regard to (a) crack front shape for

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[2]Bowker, A. H., and Lieberman, G. J., Engineering Statistics, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1972, pp. 454-458.

[3]Ibid, pp. 225-228.

the low K_{max} tests, group 3, and (b) number of fatigue cycles to initiate and grow a crack for all tests. For both of these situations, overload is a benefit, because for (a) overload leads to a more uniform crack front shape, and for (b) it leads to fewer fatigue cycles to grow the crack. In regard to the measured K_{Ic}, for the low K_{max} tests the probability that the overload and no overload data are the same population, and thus the probability that overload has no effect on K_{Ic}, is 55%. No conclusion is made from this result. However, considering that the mean K_{Ic} values are different by less than 10%, which variation is not uncommon with K_{Ic} tests, this 55% probability should cause no alarm.

3. OVERLOAD TO PREVENT CRACKS

A tensile stress overload to the area of a notch in order to prevent the growth of fatigue cracks is, like the compressive overload, not generally used. The overpressure of cylindrical pressure vessels in order to prevent crack growth is commonly done and has been studied in our laboratory.[4,5] This process, called autofrettage, involves plastic deformation near the inner radius of the cylinder which results in compression residual stress at the inner radius. This prevents the growth of fatigue cracks. Our experience with autofrettage led us to the work here with tension overloads applied to notches.

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[4]Davidson, T. E., Kendall, D. P., Reiner, A. N., "Residual Stresses in Thick-Walled Cylinders Resulting From Mechanically Induced Overstrain," Experimental Mechanics, Vol. 3, Nov, 1963, pp. 253-262.

[5]Underwood, J. H., and Throop, J. F., "Surface Crack K-Estimates and Fatigue Life Calculations in Cannon Tubes," Part Through Crack Fatigue Life Predictions ASTM STP 687, J. B. Chang, Ed., American Society for Testing and Matierals, 1979, pp. 195-210.

3.1 Test Procedure

Four specimens similar to the compact fracture toughness specimen described in ASTM Method E399 were made as shown in Figure 2. The specimens were taken from a cannon forging similar to that described earlier, except with a yield strength of 1040 MPa. The test procedure was, first, the application to two of the specimens of a tensile overload, then the fatigue loading of all specimens at a maximum load of 15.6 kN. This would correspond to a K_{max} of 56 MPa$\sqrt{m}$ if a crack were present in the specimen rather than a notch. We choose to use K to describe the loading in the tests because K includes the effect of notch length in addition to the effect of load or stress level; the full meaning of a K value is not intended since there is no sharp crack present except near the end of the tests. The value of K_{min} during fatigue loading was always one tenth of K_{max}. The initiation and growth of a fatigue crack at the notch root was monitored using a magnetic particle inspection procedure and a 10 power telescope. Crack length along the notch root, 2c, was measured, as indicated in Figure 2; measurements of and changes in 2c as small as 0.5 mm could be detected.

3.2 Results

Table IV shows the results of the tension overload tests. Specimens 11-1 and 11-2 had no overload; the first fatigue cycle was considered an overload for the purposes of comparison in the table, but the ratio of K overload to K_{max} was equal to 1.0. With no overload, 65,000 cycles were required to initiate and grow a fatigue crack to a 2c length of 2 mm, and an average of 18,000 additional cycles were required to grow the crack across the entire 10 mm thickness of the specimen.

With an overload of 1.5 times the K_{max} used in fatigue, the number of fatigue cycles required for the same amount of crack growth is increased by about a factor of 2.5. More significantly, with an overload ratio of 2.0, the fatigue life may be extended indefinitely; the test was stopped after 1,000,000 cycles with no indication of crack initiation.

Even though only four specimens were tested, the large difference in the test results clearly leads to the conclusion that, at least for the type of material and geometry tested, tensile overload of large enough magnitude can produce manyfold increases in the fatigue life of notched components.

4. ANALYSIS

Analysis of the effect of overload on crack growth from a notch can serve to identify the basic source of the effect. The following may help to accomplish this.

It is known that the primary effect of overpressure on fatigue crack growth from the inner radius of cylinders is the effect of residual stress referred to earlier. It is our contention that residual stress is the basic source of overload effects on fatigue crack growth from a notch. To test this belief the maximum stress at the notch root during fatigue loading is calculated, modified to account for residual stress, and used to estimate N_f for comparison with measured N_f.

Rolfe and Barsom[6] give a useful relation for calculating the maximum stress, σ_{max} at the root of a notch. The relation is not exact, but it can be used over a range of root radius, ρ, and it is in terms of K as determined from overall specimen dimensions and loading:

$$\sigma_{max} = \frac{2\ K_{max}}{\sqrt{\pi\rho}} \quad . \tag{3}$$

Values of K_{max} and ρ from some of the tests and the calculated σ_{max} are shown in Table V. For the compression tests the values of σ_{max} are very high due to the small ρ; in fact they are further above the material yield strength than can be expected reasonably. However, this estimate of σ_{max} is still useful as a comparative estimate of the stress at the notch, including as it does both global and local information, K and ρ, respectively.

The estimate shown in Table V of residual stress due to overload, σ_R, is simply 0.7 times the yield stress for all cases except specimen 11-3. The rational for this is that there is sufficient overload to produce a residual stress approaching the yield strength; the 0.7 factor is due to variations in the yield behavior known to occur in the type of steel used here, such as the Bauschinger effect,[7] which is a lowering of the yield strength following yielding in the opposite sense. Residual stress measurements in overstrained cylinders[4] indicate that 0.7 of yield strength is an approximate upper limit

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[4]Davidson, T. E., Kendall, D. P., Reiner, A. N., "Residual Stresses in Thick-Walled Cylinders Resulting From Mechanically Induced Overstrain," Experimental Mechanics, Vol. 3, Nov. 1963, pp. 253-262.

[6]Rolfe, S. T. and Barsom, J. M., Fracture and Fatigue Control in Structures; Applications of Fracture Mechanics, Prentice-Hall, Inc., Englewood Cliffs, NJ, p. 212.

[7]Milligan, R. V., Koo, W. H., Davidson, T. E., "The Bauschinger Effect in a High-Strength Steel," Journal of Basic Engineering, Vol. 88, June 1966, pp. 480-488.

to residual stress. For specimen 11-3, which had a smaller overload ratio of 1.5, the σ_R value shown is 0.7 times the difference between the overload stress, 1640 MPa, and the yield strength, 1040 MPa.

A hypothetical sketch of the applied and residual stress distributions near the notch is shown in Figure 3. As is shown, the amount of crack growth is considered small relative to the depth of the stress distributions. So the maximum values of stress, that is, σ_{max} and σ_R, are used to analyze the effect of overload on N_f. Since N_f in the tests was in the range of 10^4 to 10^5 cycles, the Paris-type expression for this material[5] can be used:

$$da/dN = 6.52 \times 10^{-12} \Delta K^3$$

with da/dN in m/cycle and K in $MPa\sqrt{m}$. Based on this cubic relation, a stress parameter is calculated which should be in reasonable agreement with the ratio of N_f with no overload to N_f with overload. This stress parameter, the cube of the inverse ratio of σ_{max} with no overload to σ_{max} with overload, is compared in Table V to the N_f ratio measured in the tests. The rational of this comparison is that N should vary inversely with the third power of σ, providing that the effects of overload are included in both the calculation of σ and the measurement of N. The comparison in Table V of the σ and N_f parameters is good, considering the inherent variation in fatigue data. This supports our contention that it is the residual stress due to overload which controls the fatigue crack growth from a notch.

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[5]Underwood, J. H., and Throop, J. F., "Surface Crack K-Estimates and Fatigue Life Calculations in Cannon Tubes," Part Through Crack Fatigue Life Prediction, ASTM STP 687, J. B. Chang, Ed., American Society for Testing and Materials, 1979, pp. 195-210.

5. APPLICATIONS AND CONCLUDING REMARKS

The compression overload tests showed that when a crack is required, an overload before fatigue loading is of clear benefit, both in reducing the number of cycles required to grow a crack and reducing the variation in crack front shape. These effects are more prevalent at low levels of fatigue load than at high levels. To obtain these beneficial effects, the overload-to-maximum fatigue load ratio must be high enough that the overload residual stress is not overwhelmed by the applied stress on the first fatigue load cycle. An overload ratio of 2.0 was adequate for the tests here. A related concern is that the overload is not too large. Calculation of the plastic zone size using Irwin's formula,

$$r_y = \frac{1}{6\pi}\left[\frac{K_{overload}}{\sigma_{yield}}\right]^2 \tag{4}$$

can check for an excessive overload, by comparing r_y with the amount of crack growth following overload. In the tests here for example, the largest r_y was 0.3 mm, compared with 3 mm crack growth, so the overloads were not too large.

The tension overload tests showed the clear benefit of overload in increasing the fatigue life of a notched specimen. A factor of 2.5 increase in life was seen with an overload-to-maximum fatigue load ratio of 1.5, and a factor of more than 12 increase in life was seen with an overload ratio of 2.0. In the use of tension overloads the analysis and results here indicate that two conditions may be necessary for a significant increase in fatigue life: an overload of at least twice the maximum fatigue load and an overload which produces an applied tension stress at the notch root of at least twice the material yield strength. The concern of an excessive tensile overload can be met by observing the load-deflection behavior of the specimen during overload or by calculating the bending limit load of the remaining section of the specimen ahead of the notch.

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3. Ibid, pp. 225-228.
4. Davidson, T. E., Kendall, D. P., Reiner, A. N., 'Residual Stresses in Thick-Walled Cylinders Resulting From Mechanically Induced Overstrain," Experimental Mechanics, Vol. 3, Nov. 1963, pp. 253-262.
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7. Milligan, R. V., Koo, W. H., Davidson, T. E., "The Bauschinger Effect in a High-Strength Steel," Journal of Basic Engineering, Vol. 88, June 1966, pp. 480-488.

TABLE I . TEST CONDITIONS FOR COMPRESSION OVERLOAD SPECIMENS

	Specimen Number	Specimen Depth, W mm	Compression Overload kN	Starting Fatigue Load, K_{max} $MPa\sqrt{m}$
Group 1:	42A	42.4	35.0	43.2
	42B	42.4	0	43.7
	34A	41.9	35.0	45.1
	34B	42.4	0	45.2
	25A	42.7	35.0	44.8
	25B	42.4	0	45.1
	43A	43.2	35.0	45.0
	43B	42.1	0	44.7
	28A	42.7	35.0	46.7
	28B	43.2	0	43.9
Group 2:	734	73.9	67.6	43.4
	807	74.9	0	42.4
	839	74.9	67.6	43.2
	842	75.7	0	42.4
	703	74.9	67.6	41.5
	818	74.4	0	42.1
	810	72.4	67.6	44.5
	822	72.4	0	44.5
	875	75.7	67.6	40.4
	931	74.4	0	42.6
Group 3:	851	72.4	51.6	34.7
	865	73.2	0	33.9
	852	74.2	51.6	32.3
	847	72.9	0	33.0
	004	72.4	51.6	35.4
	005	72.4	0	35.4
	943	74.9	51.6	33.8
	663	74.9	0	32.7
	846	74.9	51.6	31.8
	850	76.2	0	30.4

TABLE II. RESULTS OF COMPRESSION OVERLOAD TESTS

Test Conditions	Specimen Number	Δa, Final mm	$\Delta a_{min}/\Delta a$	N_i, Δa = .25 mm K Cycles	N_f, Final Δa K Cycles	K_{Ic} $MPa\sqrt{m}$
Group 1: W = 42 mm; K_{max} = 43 $MPa\sqrt{m}$						
$K_{overload}$ = 86 $MPa\sqrt{m}$	42A	3.3	0.57	7	14	159
	34A	3.4	0.68	5	14	148
	25A	2.3	0.78	5	12	165
	43A	2.1	0.72	5	12	163
	28A	2.2	0.80	6	12	134
$K_{overload}$ = 0	42B	2.8	0.54	11	20	152
	34B	2.8	0.73	11	19	158
	25B	2.5	0.82	11	18	149
	43B	3.0	0.85	10	20	148
	28B	3.1	0.73	8	15	137
Group 2: W = 74 mm; K_{max} = 43 $MPa\sqrt{m}$						
$K_{overload}$ = 86 $MPa\sqrt{m}$	734	2.5	0.52	4	11	138
	839	2.7	0.56	4	14	138
	703	2.6	0.58	4	12	140
	810	2.7	0.47	4	11	141
	875	2.4	0.32	4	13	144
$K_{overload}$ = 0	807	2.5	0.62	8	15	134
	842	2.4	0.32	8	15	154
	818	2.6	0.29	8	14	153
	822	3.0	0.60	10	16	136
	931	2.6	0.49	11	16	147
Group 3: W = 74 mm; K_{max} = 33 $MPa\sqrt{m}$						
$K_{overload}$ = 66 $MPa\sqrt{m}$	851	3.0	0.42	10	23	123
	858	2.7	0.47	10	24	133
	004	2.5	0.52	9	21	126
	943	2.7	0.37	10	24	134
	846	2.4	0.54	11	25	135
$K_{overload}$ = 0	865	2.5	0.10	27	35	141
	847	3.2	0.31	59	66	151
	005	3.0	0.04	31	38	137
	663	3.3	0.23	31	42	131
	850	3.5	0.18	70	78	139

TABLE III. SUMMARY AND STATISTICAL ANALYSIS OF COMPRESSION OVERLOAD TESTS

Group	Overload MPa$\sqrt{m}$	Fatigue MPa$\sqrt{m}$	Crack Growth $\Delta a_{min}/\Delta a$ μ	σ	P_a %	Fatigue Cycles N_f K Cycles μ	σ	P_N %	Fracture Toughness K_{Ic} MPa$\sqrt{m}$ μ	σ	P_K %
1	86	43	0.71	0.09	98	12.8	1.1	<5	154	13	95
	0	43	0.73	0.12		18.4	2.1		149	8	
2	86	43	0.49	0.10	97	12.2	1.3	<5	140	3	93
	0	43	0.46	0.15		15.2	0.8		145	9	
3	66	33	0.46	0.07	5	23.4	1.5	21	130	5	55
	0	33	0.17	0.11		51.8	19.1		140	7	

TABLE IV. RESULTS OF TENSION OVERLOAD TESTS

Specimen Number	$K_{overload}$ MPa$\sqrt{m}$	$K_{overload}/K_{max}$	N_i For 2c = 2 mm K Cycles	N_f For 2c = 10 mm K Cycles
11-1	56	1.0	65	84
11-2	56	1.0	65	82
11-3	84	1.5	194	214
11-4	112	2.0	>1000	>1000

TABLE V. COMPARISON OF OVERLOAD TESTS WITH ANALYSIS

	K_{max} MPa$\sqrt{m}$	ρ mm	σ_{max} MPa	σ_R MPa	$\left[\frac{\sigma_{max} + \sigma_R}{\sigma_{max}}\right]^3$	$\frac{N_f \text{ no overload}}{N_f \text{ overload}}$
Compression Overload:						
Group 1,2	43	0.13	+4260	+820	1.70	1.34
Group 3	33	0.13	+3270	+820	1.96	2.21
Tension Overload:						
Specimen 11-3	56	3.4	+1090	-420	0.23	0.39
Specimen 11-4	56	3.4	+1090	-730	0.04	<0.08

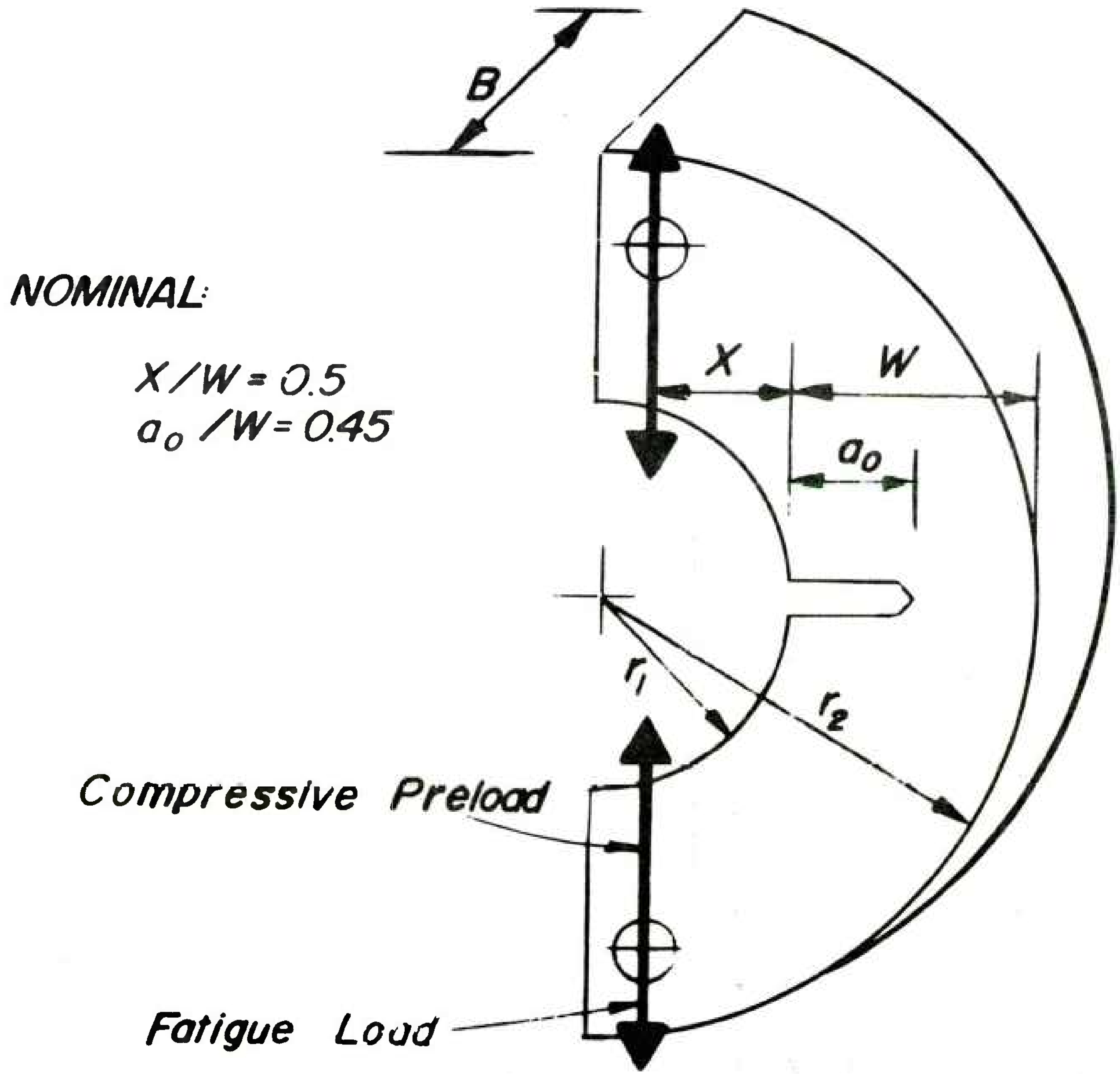

Figure 1. Compression Overload Test Specimen

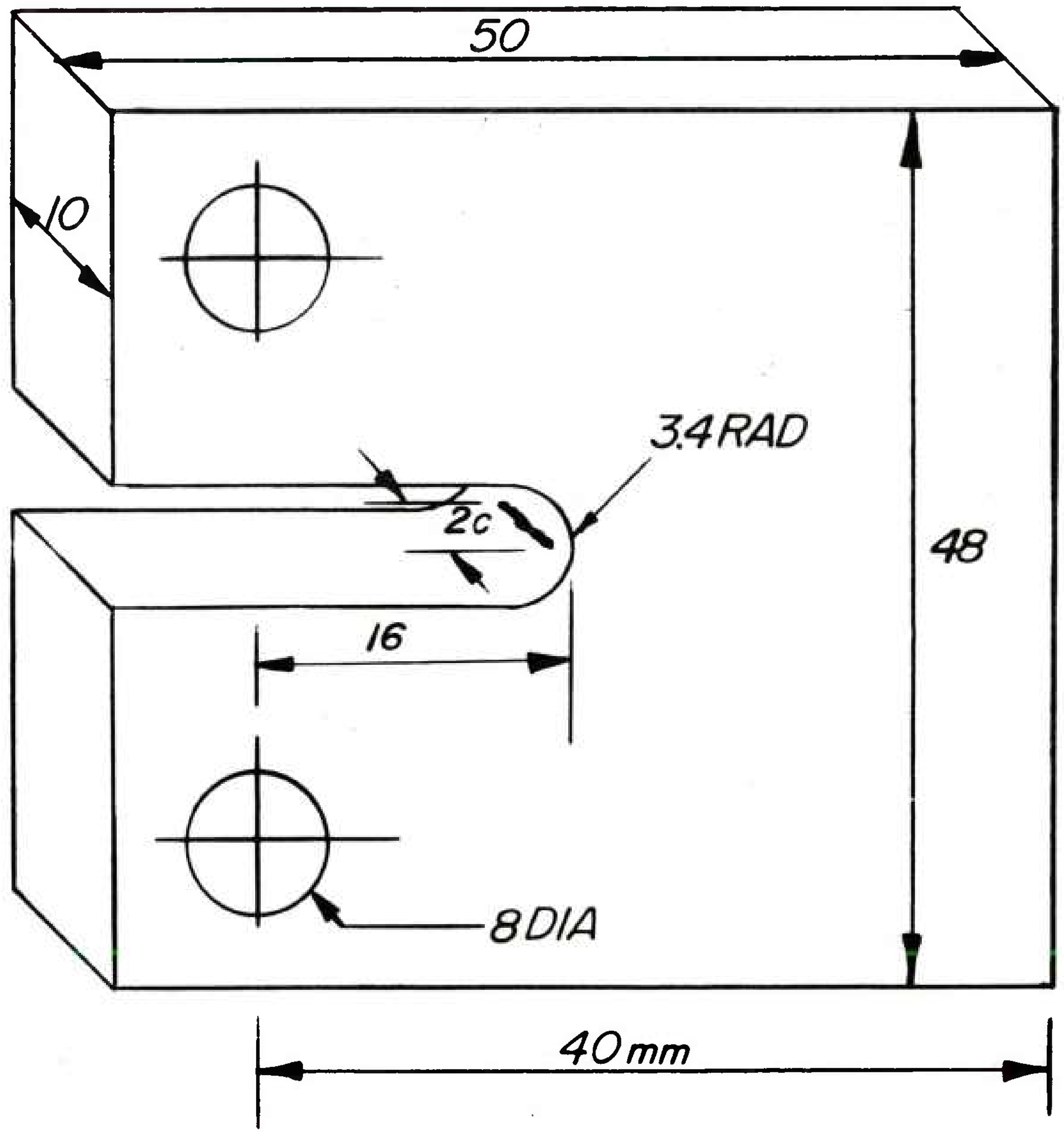

Figure 2. Tension Overload Test Specimen

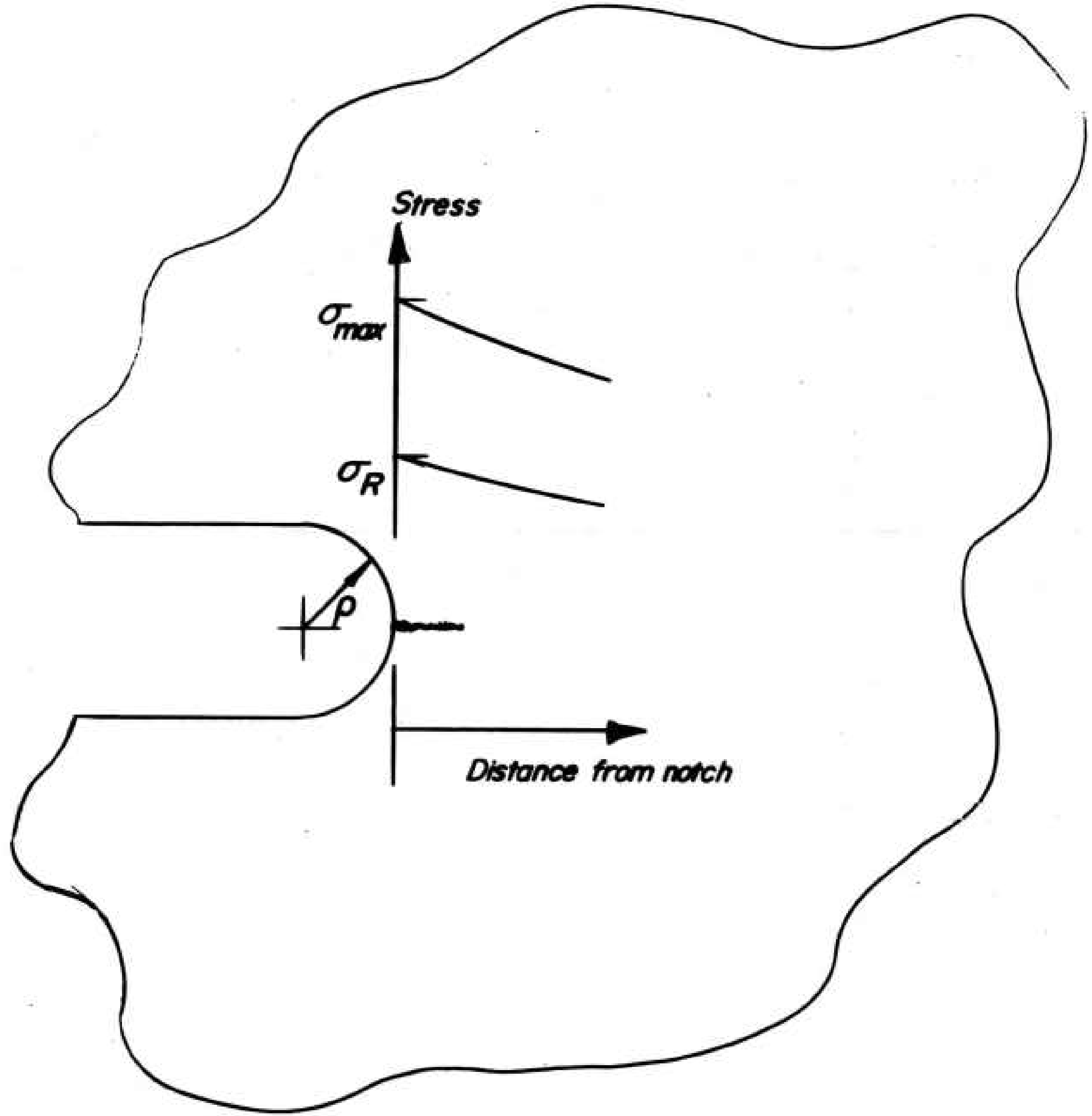

Figure 3. Sketch of Stresses Near a Notch

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